BACKGROUND PAPER ON THE ROLE OF VISUAL SYSTEM IN SPATIAL ORIENTATION/DISORIENTATION

by

Colonel Grant B. McNaughton, USAF
Chief, Life Sciences Division
Directorate Aerospace Division
Norton AFB, California

I. It has long been thought that spatial disorientation is due to conflicting inputs between the vestibular system (balance organ in the ear), the somatosensory (seat of pants and body feel) system, and the visual system. We now know that this is only part of the story. The most consistent and probably most important cause of spatial disorientation is conflict within the visual system itself, between two of its functional components.

The concept of a two mode visual system[1], although in some respects an oversimplification, is nevertheless helpful in evaluating the role of vision in spatial orientation and disorientation. Two modes are: (1) A focal mode which in general answers the question "what"; i.e., what is it we are looking at? The focal system reads instruments, identifies targets and aims the gun. Unless the focal system correctly identifies those characters on the 20/20 line, flying status is jeopardized. (2) An ambient mode which is concerned with the question "where"; i.e., where is the observer in space? Which is moving, the observer or the environment?

These two modes differ considerably along a number of dimensions. Specifically: (1) The focal mode is almost, if not exclusively visual, while the ambient mode acts in concert with the vestibular and somatosensory systems to subserve spatial orientation, balance, and motion. In effect, we have a focal visual mode which is predominantly visual, and an ambient system to which vision contributes, along with vestibular and somatosensory inputs. (2) Object recognition by the focal mode is subserved by the full range of spatial visual frequencies, whereas the ambient mode is adequately activated by low spatial frequencies typically stimulating large areas of the visual field. Whereas the focal system recognizes objects and details, the ambient system takes in the quality of the surroundings: e.g., the "wallness" of a wall, "surfaceness" of a surface, "horizoness" of a horizon, "cockpitness" of an A/C, and so forth. (3) Adequate light and refractive correction are critical for effective functioning of focal vision, but are much less important to ambient vision. The low spatial frequencies subserving ambient vision are less sensitive to degradation of image quality by reduction of luminance or refractive error. Though one can't read in a darkened room, he has little difficulty orienting, provided there is some light (see figure 1). (4) Effectiveness of focal vision depends on proximity to the visual center of the eye – the fovea. Acuity declines rapidly moving toward the periphery. To some extent, this holds also for ambient vision. However, effective activation of the ambient system depends more on the amount that is stimulated; the larger or more commanding the stimulus, the greater the response. The visual fields of the brain contain receptors activated by lines, as if "tuned" to horizon lines; the longer the line, the greater the quality of "horizoness," and the more commanding the effect.[2] (5) Focal vision typically involves active attention while ambient visual functions are more passive and reflexive in nature. Reading while walking demonstrates that

spatial orientation is adequately maintained without conscious effort despite domination of attention by the focally mediated reading task.

When analyzing the contribution of vision to spatial orientation/disorientation, it is important to consider the characteristics of ambient vision and its interaction with vestibular and somatosensory inputs. (1) Flying solely by instruments is facilitated by the wearing of a hood or "bag" which completely blocks out competing and conflicting visual stimuli. (2) By far, the most disorienting of flying situations involve:

a) Unhooded visual flight, plus

b) Lack of discernible horizon and/or reference to the earth's surface, plus

c) Conflicting or mismatching inputs to the ambient visual system producing the illusion of self-motion (vection) from external and/or internal sources, creating canopy reflections (Star Wars Effect).[3]

Examples of such disorienting situations include:

a) Night formation weather.

b) Flying in and out of the weather, then suddenly entering total IMC without having first transitioned to instruments.

c) Night ordnance deliveries under the flares.

d) Flying at high altitude on a clear moonless night, stars blending with ground lights, and no discernible horizon.

e) Night IFR with "Star Wars Effect" canopy reflections.

f) Common to these situations is wide area stimulation of the ambient visual system producing the illusion of self-motion (vection) or Star Wars Effect.

Though unparalleled for day VFR flying, the bubble canopies of modern fighters like the F-16 render them human factors nightmares when the sun goes down. Flying "enhanced night role,"[4] the higher the pilot sits, the greater the disorienting stimuli to his ambient visual system.

Though there is considerable individual variability, the pilot's propensity for disorientation appears to be a function of the ratio of matching to mismatching, or conflicting, cues. To effectively combat spatial disorientation, regardless of cause, the pilot must establish visual dominance on valid cues. In an aircraft under IMC, the only valid cue available is the attitude indicator. The bigger the attitude indicator, the more commanding and effective it is.

a. All standard attitude indicators (AI) have the same defect from the human factors standpoint: that is, the sensing is backwards. (The most commanding portion of any gauge is the part that moves.) In the standard AI, the part that moves is the horizon. In a left bank, the horizon is tilted right; in order to erect the horizon, i.e., roll it to the left, the stick must be moved to the right, and vice versa.

Since this sensing is backwards, the pilot must undergo a learning process in order to correctly use the AI. Typically this involves a second-order cognitive process such as imagining oneself viewing the world through a porthole the diameter of the AI, and that the 2" or 3" width of horizon is all that one can see. If it were long enough to be considered as the true horizon (instead of a mere symbol of the horizon) no interpretation would be required. As it is, the diminutive proportions of the AI horizon render it a symbol of the true horizon, requiring mental activity for interpretation. In a panic situation, pilots commonly roll the wrong direction.

b. To be more effective as an attitude indicator, the horizon line should generate more impact on the ambient visual system. It should be longer and more commanding, and have more quality of "horizoness."

c. In order to compete effectively with the mismatching ambient visual inputs of a disorienting Star Wars Effect situation, the ratio of artificial horizon length (matching cues) to ambient visual area exposed to illusory stimuli (mismatching cues) should be higher.[5] The optimal ratio has not yet been established. Pilots instinctively improve this ratio under disorienting circumstances by leaning forward, getting as close as possible to that almighty attitude indicator, and simultaneously blocking out the disorienting stimuli. (They might also improve circumstances by wearing blinders.)

Whereas overwhelming stimuli to the ambient visual system produce one type of confusion, namely the vection illusion, lack of stimuli to the ambient system tends to produce the opposite: namely, the illusion that the viewed object is moving.

a) It is well known that a stationary light viewed in darkness will appear to move (auto-kinetic effect). A similar effect can occur during a night approach over a surface totally devoid of light or reference cues ("black hole") when all the pilot can see is the somewhat distant runway environment. As he maneuvers and changes his relative viewing angle, the pilot may likely sense that the runway environment, not he, has moved, thus generating some confusion.

b) Additionally, it is absolutely impossible to orient oneself to a point source of light, either attitude-wise or distance-wise without an adequately commanding attitude indicator near his line of view. A pilot shooting this type of approach can very quickly attain unwanted attitudes.

"Magic Carpet" Effect:[6] Aircraft lacking a readily visible attitude reference predispose to the effect of sitting out on a "magic carpet," with resultant difficulty in precise attitude control.

a) Design features leading to this include:

(1) Cockpit well forward of the wing.
(2) Stubby or down-sloping nose.
(3) Bubble canopy, low canopy rail, and reduction or absence of reference cues on the canopy, such as bows.

b) Difficulty in night/weather formation flying in an aircraft such as the F-16 would be expected. With loss of distance/depth perception at night, how can the wingman nail his attitude with sufficient precision to avoid a mid-air?

II. Wide Field of View Horizon or Peripheral Vision Horizon Devices (PVHD)

Principle. A horizon that is wide enough can provide orientation cueing directly to the ambient visual system, the orientation "core," without the necessity of secondary cognitive processing, or thinking. It gives the pilot a horizon he doesn't need to look at; it is just "there." In other words, attitude information is provided automatically at a reflex level. This frees the focal visual system for tasks requiring acuity and attention. (The brain has the capability of processing inputs simultaneously or "in parallel" rather than serially, providing there is a suitable format for presentation. The PVHD takes advantage of that capability: it permits "parallel" processing by the brain.) Studies have shown that, during flight under IMC, the eye spends 50 to 90% of its time dwelling on the attitude indicator.[7] A wide FOV horizon can relieve that burden, thus reducing cockpit workload significantly. The wide horizon allows exceptionally precise attitude control, both in pitch and in roll. Confidence in orientation theoretically derives from the ambient system: the wide horizon has been reported to promote a feeling of psychological confidence in attitude control. Furthermore, attitude can be monitored subliminally, without direct viewing, when look-ing away, such as when flying formation, or going heads down in the cockpit.

Purposes of PVHD:

(1) Prevent spatial disorientation.
(2) Reduce cockpit workload.
(3) Improve precision in attitude control.
(4) Enhance pilot confidence in attitude control — thus enhancing his mission effectiveness.

Experience with PVHD:

T-37B — NASA-Dryden FRC.[8] An artificial horizon projector was constructed from an old 3-axis eight ball by cutting a slit in the horizon, replacing the yaw axis with a mono-filament incandescent light, the filament paralleling the slit, and reversing the roll leads. The projector was mounted between the occupants and projected a "light bar" approximately 1½" X 24" onto the instrument panel. Light intensity was low requiring a dark night for proper use, but the horizon worked as advertised. It provided excellent subliminal attitude information without the pilot having to look at it, and precise attitude control during precision approaches, even with the ADI taped over. Center-mounting revealed a problem: with the roll-axis off center, roll would create the illusion of pitch. For example, in a left roll, the left-seater felt himself pitching down, the right-seater up.

Malcolm Horizon Peripheral Vision Horizon Device (PVHD). Dr. Richard Malcolm, a Canadian physiologist, developed the device bearing his name, using a red laser as the light source. Versions have been flown in several of our aircraft: the Lockheed Jetstar, USAF aircraft that flies high and fast, a USAF Test Pilot School RF-4C, and the LANTIRN A-10. A conference on the Malcolm Horizon held at NASA-Dryden FRC, 15-16 Mar 83, revealed these findings:

High and fast aircraft:[9]

(1) Enhances precise attitude control, especially in pitch.
(2) Prevents spatial disorientation.
(3) Reduces cockpit workload.
(4) Enhances pilot confidence.

USAF Test Pilot School RF-4C:[10] Mounted in rear cockpit which is hooded. Test plan involves attempts to disorient the GIB under the hood, then let him recover from unusual attitude using the PVHD; also to practice precision ILS approaches with PVHD. There were several criticisms:

(1) It was difficult to disorient the GIB under the hood which, considering the role of ambient vision in disorientation, is to be expected.

(2) The PVHD is used to prevent SDO, not to recover from unusual attitudes — although it does appear to facilitate unusual attitude recovery. (It incorporates a "sky-pointer" so the pilot will recover right-side-up.)

(3) Quality of projected horizon needed improvement: bright dots were substituted for the line at lower power settings, and when the line appeared (connecting the dots) it wavered continuously.

(4) Horizon was only 18" wide. It did not seem commanding enough and might not be monitored easily enough while looking outside flying formation, or looking inside heads down. It was much easier, however, to sneak-a-peek at the PVHD than to the ADI, and attitude control was exceptionally precise. Furthermore, the gadget worked as advertised through 360° loops and rolls.

(5) Comment: The PVHD is exceptionally commanding. Therefore, it is essential that it not provide erroneous information — i.e., that sufficient fail-safe be incorporated.

LANTIRN A-10:[11] Evaluation inconclusive but pilot use of PVHD low because:

Display problems:

(a) Cockpit has low ratio of instrument panel to windscreen: there is not sufficient instrument panel surface on which to project the PVHD.

(b) Pilot sits high; PVHD is too low to be monitored adequately by the peripheral visual fields.

(c) Laser reflections off certain instrument surfaces would occasionally hit the pilot's eye "like a fire-warning light," causing distraction and annoyance.

LANTIRN already has a 25-30° wide FOV HUD upon which the FLIR projects the actual horizon. Provided VMC, the pilot has the actual horizon right there at eye level. He doesn't need the PVHD. Therefore, most project pilots turned it off after several rides. (What the HUD didn't have was a wide CRT-generated horizon line for use in IMC or over mountain terrain, etc.)

(d) Cockpit compatibility cursory evaluation. Following the conference, several participants (Mr. Einar Enevoldson, NASA-Dryden test pilot; Mr. Art Kennedy, Garrett of Canada which manufactures the Malcolm Horizon; and Col. Grant McNaughton, AFISC/SEL) evaluated the PVHD in three cockpits at NASA, at night: F-111, F-15, and AFTI F-16.[12]

(1) F-111. With plenty of instrument panel available, the PVHD appeared quite compatible. Canopy reflections were no problem. Centering roll axis produced the roll-pitch illusion seen in the T-37. If used in the F-111, roll axis should be centered in front of the pilot.

(2) F-15. There appears to be sufficient instrument panel to display the PVHD, though the pilot's line of sight is somewhat higher. Monitoring is possible during heads-out simulating formation flying, as well as going head-down. There were occasional annoying reflections off certain instruments though none off the HUD or canopy. Interestingly, the PVHD does not show up when projected onto multi-function display (MFD) surfaces, though this could apparently be corrected with a different surface coating.

(3) AFTI F-16. F-16 instrument panels vary from block to block and this one is different yet. They're all similar when it comes to the Malcolm Horizon:

(a) Surface on the upper portion of the panel is limited and, that surface which is available is broken up by the HUD control panel which juts out 5 - 6" from the plane of the instrument panel.

(b) The PVHD does appear to be compatible with the F-16 cockpit if it were projected below the HUD control panel over the bottom row of instruments: airspeed indicator, ADI, and (in block 10) the altimeter. It would then be quite useful to a pilot while he is head-down.

(c) Aimed too low, the PVHD strikes the pilot's knees which jut up above displays on the center pedestal due to the tilt-back seat.

(d) Canopy reflections might be a problem. PVHD occasionally generated reflections.

III. Proposed Improvement for the F-16.

That the F-16 has SDO problems at night and in IMC has been amply demonstrated from the following mishaps.[13]

82-11-08 MacDill: Night, range
Pilot: Former T-38 IP; TT: 1269 hrs;
F-16: 745 hrs, all in block 10 aircraft;
30/60/90: 19/41/57 hrs.

During pulloff from a night radar lay down, element made pre-briefed lead change. Lead called, "Passing on your left," just as mishap aircraft entered cloud. Mishap pilot called "Two's IMC"; 23 seconds later, two's response to whether he had visual contact was, "Negative, I'm blind" (indicating VMC but no tally on lead); then five seconds later, "Standby" (indicating increased workload distraction, possibly from cockpit warning lights). He then emerged 13-15 seconds later in a shallow inverted right bank, to crash. HUD attitude indications at the moment of entering IMC, and at the instant of impact, may have been confused, as may have been the ADI. (There was a mismatch between capture marks on the primary ADI (115° bank) and impact attitude (150° right bank).) Note the barrel on the primary ADI is less than 2" in diameter; the ADI is located down between the knees, 24" - 34" from the eye, depending on seat adjustment. At impact, A/C fail and FCS disc lights were illuminated, possibly distracting the pilot. The aircraft also had a documented interior lighting deficiency. (The SIB questioned the pilot's acceptance of the A/C for night flight.)

This pilot was most likely attempting to locate his leader, cope with cockpit warning lights, and perhaps, simultaneously adjust cockpit lighting. He was quite likely referring to the HUD for attitude information. He likely never felt disoriented nor even questioned his attitude, despite having rolled right, well past the

vertical. Had he looked at the primary ADI, the picture may not have alerted him that he was, in fact, inverted due to lighting, competing reflections, canopy glare, etc. Many squadron mates attested that the F-16 aircraft is quite disorienting at night.

82-11-15 Kunsan. Rather experienced IP:
TT: 2276 hrs; F-16: 578 hrs; 30/60/90: 15,25,36 hrs.

Pilot was lead of a three ship low level navigation mission to the range. While proceeding VMC between cloud layers, lead announced, "Lead has a problem; two, follow," whereupon lead rolled smartly into a left turn, estimated at 5 G's, presumably to RTB. In so doing, he entered a cloud deck, was noted to reemerge briefly, then enter another deck. He impacted within 13-20 seconds, in cloud-obscured mountains, in a steep dive, at a high velocity, without a further call or attempt to eject. Findings included a mismatch of 105° between ADI (65° ND) and Standby Attitude Indicator (40° NU). Unable to determine whether lead's "problem" was physical or aircraft-related, the SIB attributed the mishap to SDO. (However, pilot incapacitation from some factor such as G-induced loss of consciousness could not be ruled out.) Many squadron mates there attested that the F-16 was quite disorienting in IMC.

82-12-01 Hahn. An inexperienced pilot:[14]
TT: 333.3 hrs; F-16: 140.5 hrs; 30/60/90: 15.5, 31, 39) whose total flying time in actual IMC was only about one hour, was sent out on a night solo aerial refueling mission. After aerial refueling, his primary instrument lights were discovered inoperative. He used instrument flood lights for illumination during remainder of the flight. He handled the mission uneventfully 'til recovery. During a right descending turn to final, he experienced SDO. The SDO, alternate cockpit lighting, and unfamiliar approach with high cross-winds to an ill-defined runway all contributed to task-situation. He then was IMC in icing conditions from 8 to 4 miles out and stated he had vertigo in the clouds. He had never landed on this runway, day or night, and was unfamiliar with its environment. The terrain over which the approach was flown was a lightless, cueless black hole. Breaking out of the weather well left of course, the pilot acquired the VASI's, red/white, and began to correct, using only AOA and VVI. He then heard a distinct and totally unfamiliar "thump," which distracted his attention 6 - 8 seconds. By the time he rechecked ahead, his sink rate was excessive. Despite going to AB, the aircraft struck an ILS antenna, lost hydraulics, and pitched-up out of control. The pilot ejected unharmed. This pilot was basically over-committed, tasked by the lighting problem in an environment lacking in sufficient valid cues to his ambient orientation system. He was set up for the confusing Target-Displacement Illusion and auto-kinetic effects, plus one additional systematic tendency on night landings: the tendency to undershoot night visual approaches. (Because the eye attempts to maintain the same sight picture, or keep the same angle subtended between far and near ends of the runway, one tends to fly the arc of a circle, the chord of which is the visible portion of the runway. The result is a "banana shaped" approach, convexity downward, with a tendency to land short.)[19] The great majority of interviewed squadron mates also complained of vertigo on night weather approaches. A vertiginous pilot is a compromised pilot. Quite possibly, an unrecognized unusual attitude contributed to this pilot's critical loss of altitude.

Cockpit configuration differences among different F-16 blocks: differences between instrument configurations was mentioned as a possible contributing factor in a recent mishap (F-16A 83-01-09, Hill).[13] The pilot was a highly experienced SEFE (TT: 3378 hrs; F-16: 423/7 hrs; 30/60/90: 14/7, 30, 50 hrs) on a day three-ship SAT mission to the range. Seven of his previous eight flights had been in block 15

aircraft, in which the altimeter sits adjacent to the radar scope (above, left). The mishap aircraft was from block 10, in which the altimeter is above the right rudder well.

On the mishap flight, this pilot entered IMC and became separated from his element. He selected autopilot; but with insufficient thrust, it allowed a 3800 foot descent, which went undetected over approximately 50 seconds. At impact there is evidence the pilot was in the process of changing TACAN frequencies, presumably to locate his element — though he never quite reached the target frequency. What he was doing the rest of the time is unknown. Perhaps he was searching for his element on the radar scope. In a block 15 he might have noted the altimeter unwinding.

Glare at night interfering with outside view:

The "enhanced night role" of the F-16 has generated an increased night flying commitment involving formation flying and target acquisition.[4] Both involve outside viewing which is hampered by canopy glare and reflections. The problem appears generic — related to the shape of the canopy. Some improvement occurs when turning down all lights.

Location of critical flight instruments.

Location of the Standby Attitude Indicator (SAI): On block 10/15 aircraft, the SAI is beneath the right glare-shield, difficult to view unless seat is moved down or neck bent around. In the block 25 cockpit, the SAI is partially obscured by the Data Entry Display[15] in its present cockpit with the ADI. Furthermore, searching for it upsets the normal instrument composite cross-check pattern. The logical place for the SAI is next to the ADI,[16] where failure of one would be picked up immediately and composite cross check not compromised. Ideally, both instruments should be larger and more commanding. (Of incidental interest, the AFTI F-16 doesn't even have an SAI.)

HUD symbology on the USN McDonnell — Douglas/Northrup F/A-18[17] is of some interest. The USN considers the "HUD" or its powerful capability as a primary flight reference, and have developed it as such. Safety record of the F/A-18 has been very good to date with only two losses: an engine explosion and a spin, neither due to SDO.

(1) HUD symbology incorporates a wider, more commanding horizon line that cannot be decluttered from the display (nor can other primary attitude reference information be decluttered).

(2) Pitch ladders were said to be angled from their centers, forming an arrow that points toward the horizon lines — showing the pilot immediately which way to roll to get wings level — considered very helpful in unusual attitude recoveries. (Telecon with a former USN F-18 test pilot produced this info. However, I examined an F-18 HUD at Patuxent River NAS on 12 April 83[18] and the pitch bars appeared to be straight. Nevertheless, shaping them like "chevrons," aiming toward the horizon, strikes me as a worthwhile idea.)*

*On 13 April 83, I examined an F-14 cockpit in the Oceana NAS Air-to-Air Simulator. Horizon is clearly depicted on a rectangular CRT, which is almost 6" wide. The horizon is full width; sky above is clear, surface below is hatched. It appears very commanding.[18]

(3) HUD symbology can be displayed on the right and/or left MFDs, thus getting the pilot heads down, out of the disorienting visual environment (where it belongs, for the majority of IMC flying).

Proposals to help prevent SDO and reduce pilot workload in the F-16.

(1) Widen horizon line to full width of HUD for heads-up SDO prevention.
(2) Consider PVHD for F-16 for heads-down SDO.
(3) Train pilots to cope more effectively with SDO.
(4) Study methods of reducing canopy glare without seriously compromising inside reading or outside viewing.
(5) Strongly consider side-by-side placement of ADI and SAI.
(6) Evaluate ideas incorporated by the USN in the McDonnell-Douglas/ Northrup F/A-18 HUD and in the Grumman F-14 instrument panel CRT.

a. Making HUD symbology primary flight reference.
b. Display HUD on MFD.
c. Widen horizon line.
d. Angle pitch ladders like chevrons to point toward horizon line like arrows for aid in unusual attitude recoveries.

(7) Reduce glare and reflections on canopy via appropriate shielding.

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